Agricultural and Forest Meteorology 266–267 (2019) 119–128

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Ridge-furrow full film mulching: An adaptive management strategy to reduce irrigation of dryland winter rapeseed (*Brassica napus* L.) in northwest China

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ARTICLE INFO

Keywords:
Adaptive management
Dryland agriculture
Ridge-furrow film mulching
Supplemental irrigation
Winter rapeseed

ABSTRACT

Ridge-furrow full film mulching (RFFM) has been widely adopted as a water-saving and yield-improving planting pattern in arid and semi-arid regions. Whether or not RFFM can replace the conventional flat planting pattern (FP) with supplemental irrigation in dryland farming has not been tested. Moreover, the effects of reducing irrigation frequency and amount on crops in dryland farms under different rainfall years (dry, normal or wet years) remain unknown. Present study selected winter rapeseed (*Brassica napus* L.) as a test crop for a three-year field experiment to investigate the irrigation water-saving potential of RFFM. Six treatments: 1) FP without irrigation (FP0); 2) FP with 30-mm irrigation at the overwintering stage (FP1); 3) FP with 30- and 60-mm irrigation at the overwintering and stem-elongation stages, respectively (FP2); 4) FP with 30-, 60- and 60-mm irrigation at the overwintering, stem-elongation and flowering stages, respectively (FP3); 5) RFFM without irrigation (RFFM0); and 6) RFFM with 45-mm irrigation at the flowering stage (RFFM1) were conducted to explore their effects on root and shoot biomass, nutrient uptake, yield, oil production, evapotranspiration (ET) and water use efficiency (WUE). The results indicated that RFFM0 significantly promoted root and shoot biomass accumulation and nutrient uptake. Thus it significantly improved yield by 23.7–39.0%, oil production by 26.8–43.3% and WUE by 71.3–86.5%, and simultaneously decreased ET by 21.2–29.7% in comparison to FP0 and FP1 in dry, normal and wet years. Furthermore, the yield-increasing effect in RFFM0 was nearly equal to FP3 in the normal rainfall and wet years, and was equivalent to FP2 in the dry year. Yield and oil production in RFFM1 were significantly higher than in RFFM0, and were commensurate with those in FP3 in the dry year. Therefore, RFFM reduced a two-time application with total 90 mm irrigation water in a dry year, as well as a three-time application with total 150 mm irrigation water in normal rainfall and wet years for dryland winter rapeseed. Overall, RFFM is a promising adaptive agronomic strategy to apply in dryland regions to sustain food security, and cope with water scarcity, a potential threat to dryland farming due to climate change.

1. Introduction

The concentration of CO_2, CH_4 and nitrogen oxides in the global atmosphere has rapidly increased since 1975, and the atmospheric CO_2 concentration in the mid-21st century is predicted to reach 550 μmol mol^{-1} (Houghton et al., 2001; Prentice et al., 2001). The increase of atmospheric CO_2 concentration has caused global climate warming, changes in precipitation amount and pattern, and, consequently, increased ecological and agricultural demands for water (Qin, 2002). Water shortages could become a worldwide problem, and together with population growth and industrial development, the gap between the supply and demand of agricultural water-use will widen (Shen and Su, 1998). Under the dual pressure of water shortage and population increase, how to ensure food security will be a major problem in providing for the growing human population in the future (Parry et al., 2005).

Presently, the potential for increasing grain production in irrigated agriculture has reached a high and stable plateau, thus it is difficult to further increase total grain yield by increasing the per unit area yield of irrigation districts in China (Wang et al., 2015a, b). Therefore, developing dryland agriculture will be the primary direction and is of vital significance to ensure food security in China and around the world in

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https://doi.org/10.1016/j.agrformet.2018.12.009
Received 29 September 2018; Received in revised form 28 November 2018; Accepted 16 December 2018
Available online 21 December 2018
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Table 1
Mean annual meteorological data at the experimental site and the properties of the topsoil (0–30 cm) in the experimental field.

Item	Value	Annotation
Meteorological properties		
Frost-free period (d)	210	
Sunshine hours (h)	2164	
Mean annual air temperature (°C)	12.9	Air temperature is usually lowest in January
Mean annual pan evaporation (mm)	1500	
Mean annual precipitation (mm)	632	About 60% is concentrated from July to September
Soil properties (0-30 cm)		
Dry bulk density (g cm^{-3})	1.4	
Field capacity (%)	24.0	
Permanent wilting point (%)	8.5	
Soil organic matter (g kg^{-1})	12.2	Determined by dichromate wet oxidation
Total nitrogen (g kg^{-1})	0.9	Determined by Kjeldahl distillation-titration
Alkali hydrolyzable nitrogen (mg kg^{-1})	76.0	Determined by alkaline hydrolysis diffusion
Olsen phosphorus (mg kg^{-1})	25.2	Determined by molybdenum-blue colorimetry
NH_4OAc-extracted potassium (mg kg^{-1})	133.0	Determined by ammonium acetate extraction/flame photometry
pH	8.1	

the future. In China, dryland regions accounts for 65% of the total arable land and contributes to the majority of the nation's food production (Deng et al., 2006). However, strongly limited by the harsh natural conditions (uneven rainfall distribution and high evaporation) of drylands, crop yields are very low, for example, 1500–3000 kg ha^{-1} of spring wheat and 2500–3500 kg ha^{-1} of maize (Hu et al., 2009). Therefore, supplemental irrigation is necessary to ensure high crop production in dryland farms. Despite that supplemental irrigation can substantially improve crop yield in dry regions, low irrigation water use efficiency (WUE) of crops, however, has caused severe environmental issues, such as groundwater decline, drying rivers, seawater intrusion and soil salinization as reported in China, Australia and the Mediterranean region (Deng et al., 2006; Cudennec et al., 2007; Narayan et al., 2007). The challenges facing dryland crop production have been further amplified by climate change, especially more frequent occurrences of drought. Most climate models have demonstrated that climate change will be more detrimental to dryland agriculture than irrigated agriculture (Piao et al., 2010). Therefore, the current problems to be solved for dryland farming mainly lie in two aspects. One aspect is to improve productivity levels without over-exploiting scarce water resources, and a key strategy is to increase WUE, especially rainwater use efficiency. Another aspect is to steadily improve the adaptive capacity of dryland agricultural systems to climate change (Wang et al., 2015a, b).

Rapeseed (*Brassica napus* L.), as an important source for producing vegetable oil and biodiesel, is widely cultivated throughout the world (Zhang et al., 2012). As one of the leading countries for rapeseed production, China generated an annual average of 12.6 million tons of seeds from 2001 to 2014 (FAOSTAT, 2016). In China, winter rapeseed is mainly cultivated in the Yangtze River basin, but its cultivation has expanded northward and westward, and the planting area has been rapidly increased from last decades with the rising winter temperatures in arid and semiarid regions of northwest China (Yin et al., 2010; Zhang and Wang, 2012). Yields, however, have always been low and unsteady due to frost, drought and poor WUE (Jing and Dong, 2004). Agricultural practice must be studied and adopted to improve rapeseed production due to the increasing demand for vegetable oil and fuel from the expanding population and developing economic, and to the limited arable land worldwide (Rondanini et al., 2012).

The ridge-furrow film mulching (RFM) planting pattern, where ridges are mulched by plastic film that serve as runoff areas and furrows serve as water-infiltration and planting areas, has been demonstrated to be a useful method to improve crop productivity in arid and semi-arid areas (Tian et al., 2003). Because of the hydrophobic nature and impermeability of the plastic film, any amount of rainwater falling onto mulched ridges can easily flow down the slope and infiltrate soils in the furrows through seepage holes in the film (Gu et al., 2016). In addition, RFM, especially the ridge-furrow full-film mulching (RFFM) planting pattern, can significantly increase topsoil temperature and reduce soil water evaporation. Gu et al., (2016) found that RFFM significantly improved rapeseed yield and WUE by 47.8% and 75.0% compared to those under conventional flat planting pattern without irrigation in semiarid dryland regions of the Loess Plateau, China. RFFM has also been shown to significantly improve yield and WUE for maize (Mo et al., 2017), potato (Qin et al., 2014), proso millet (Zhang et al., 2017), and oat (Qi et al., 2015) in other dryland regions benefiting from the alleviation of hydrothermal limitations. Though RFFM has been shown to significantly improve crop yield and WUE, whether RFFM is a better strategy or not than supplemental irrigation to improve yield and WUE for dryland farming remain an unanswered question.

Present study established winter rapeseed crops at a typical dryland region in northwest China from 2014 to 2017. The objectives of this study were: 1) to test if RFFM could replace irrigation or not in dryland agriculture; 2) to determine how much RFFM can reduce the need for supplemental irrigation, in terms of amount and frequency, in years of different levels of rainfall (normal, wet and dry); and 3) to identify if RFFM is an appropriate adaptive agronomic strategy in dryland regions in light of potential threats to dryland farming from climate change.

2. Materials and methods

2.1. Experimental site

The field experiment was conducted at the irrigation station (34°18′N, 108°24′E; 521 m a.s.l.) of Northwest A&F University, Yangling, located at the southern part of the Loess Plateau in northwest China, a typical dryland agriculture region. Winter rapeseed was grown over three growing seasons, from September 2014 to May 2017. Mean annual meteorological data at the experimental site and the properties of the topsoil (0–30 cm) in the experimental field are briefly described in Table 1.

2.2. Experimental design and field management

The field experiment comprised two planting patterns: conventional flat planting pattern (FP; Fig. 1a) and ridge-furrow full film mulching planting pattern (RFFM; Fig. 1b). Winter oilseed rape crops were irrigated at the over-wintering, stem-elongation and flowering stages, according to the local irrigation regimes of the high-production winter rapeseed fields. Four irrigation levels were conducted for FP (Table 2): no irrigation (FP0); irrigation of 30 mm applied once at the over-wintering stage (FP1); irrigation of 30 and 60 mm, each applied once, at the overwintering and stem-elongation stages, respectively (FP2); and irrigation of 30, 60 and 60 mm, each applied once, at the

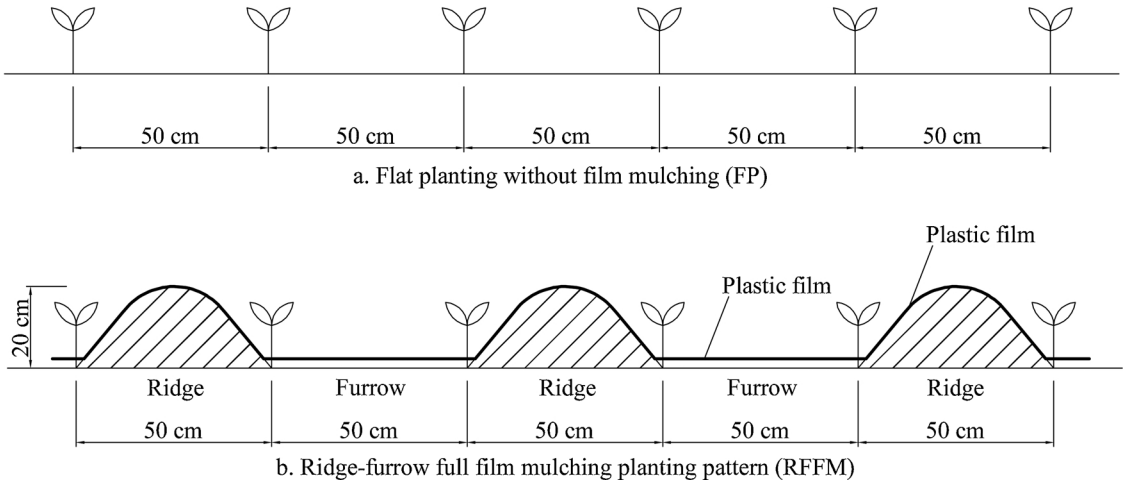

Fig. 1. Diagram of the two planting patterns used over the three growing seasons.

Table 2
Irrigation times and irrigation amount under different treatments over the three growing seasons.

Treatment	Irrigation times	Irrigation amount (mm)			Total irrigation amount (mm)
		Over-wintering stage	Stem-elongation stage	Flowering stage	
FP0	0	0	0	0	0
FP1	1	30	0	0	30
FP2	2	30	60	0	90
FP3	3	30	60	60	150
RFFM0	0	0	0	0	0
RFFM1	1	0	0	45	45

overwintering, stem-elongation and flowering stages, respectively (FP3). Two irrigation levels were conducted for RFFM (Table 2): no irrigation (RFFM0) and irrigation of 45 mm applied once at the flowering stage (RFFM1). Thus, six treatments, each with three replicates arranged in a completely randomized design, were established for the three growing seasons. Each plot, 4 m × 5 m in size, was protected by a 0.5 m bund and buffered by a 1-m-width access pathway.

As shown in Fig. 1, RFFM was formed by alternating ridges (0.5 m wide and 0.2 m high) and furrows (0.5 m wide) with film mulching on both ridges and furrows. The transparent polyethylene sheet (0.8 m in width and 0.008 mm in thickness) was applied to cover the entire soil surface of a plot, and the joints were stabilized by laying soil on the film surface. Additional soil bands with approximately 2-m interval were pressed to prevent wind from blowing away the plastic sheets. A series of small holes were made every 0.3 m in the sheets to permit rainwater or irrigation water to infiltrate the soil.

Prior to establishing the RFFM and FM treatments, basal fertilizers of urea (N ≥ 46%), calcium super-phosphate (P_2O_5 ≥ 16%), potassium sulphate (K_2O ≥ 51%) and borax (B ≥ 11%) were broadcasted at rates of 180 kg N ha^{-1}, 90 kg P_2O_5 ha^{-1}, 120 kg K_2O ha^{-1}, and 15 kg B ha^{-1}, respectively. Then the field was ploughed and the plots were divided. Subsequently, the plastic film-covered ridges and furrows were established (Fig. 1b). Seeds of shaanyou No. 107, a local variety, were sown (0.5 m in row spacing, approximate 0.15 m in plant spacing, and 5 mm in depth) through the small holes made in the plastic film in each plot on 21 September, 16 September and 10 September in 2014, 2015 and 2016, respectively. Emerged seedlings were manually adjusted to ensure that they grew through the holes rather than under the plastic film. Seedlings were also thinned to a final plant density of about 154 000 plants ha^{-1} at the fifth-leaf stage. The plastic sheets were removed and recycled after the crops were harvested on 23 May, 20 May and 23 May in 2015, 2016 and 2017, respectively. Over the three growing seasons, irrigation at the over-wintering, stem-elongation and flowering stages occurred on 15 December, 1 March and 15 April (10 April in the 2015–2016 growing season), respectively. The irrigation water was supplied from a pump outlet to each plot using plastic pipes, and a flow meter was used to measure the amount of water applied. Other field management procedures, including weed control and application of pesticides, were conducted to maintain relatively healthy crops and avoid unnecessary yield loss.

2.3. Measurements and methods

2.3.1. Shoot dry matter

Plants from 1 m^2 of each plot were cut at ground level to determine shoot dry matter. Individual plants were separated by organ (leaves, stems and pods), dried in an oven for 30 min at 105 °C to deactivate enzymes, and then dried at 75 °C until a constant weight. Then the dry leaves, stems and pods were weighed, and the shoot dry matter was calculated as the sum of each organ weight.

2.3.2. Nutrient uptake

After the shoot dry matter was determined, the dry leaves, stems and pods were digested with a H_2SO_4-H_2O_2 mixture after the samples were ground and sieved. The nitrogen (N) and phosphorus (P) contents were determined with an automated continuous-flow analyzer (AA3, Seal, Norderstedt, Germany). The potassium (K) content was measured using a flame photometer (Hitachi Z-2000, Tokyo, Japan). Total N, P and K uptake was calculated by multiplying the dry weight by the N, P and K contents in each organ, respectively.

2.3.3. Root parameters

The entire root systems of five individuals were sampled from each plot using the monolith method (Böhm, 1979) at harvest. The holes for digging the roots were approximately 0.3 m (length) × 0.3 m (width) × 0.3 m (depth). After the roots were collected, lateral roots were removed from the taproots with scissors. The length and diameter of taproots were then determined using a ruler and vernier caliper, respectively. After morphological measurements were collected, taproots in each plot were dried in an oven at 75 °C until a constant weight, and the taproot dry weights were then measured.

Lateral root distribution was determined using an auger method (Böhm, 1979) at harvest. Five soil cores (about 8 cm in diameter) were taken from each plot at depths of 0–0.1 m, 0.1–0.2 m and 0.2–0.3 m in the middle of two adjacent plants within a row. Roots in the cores were picked and separated from the soil, dried in an oven at 75 °C to a constant weight, and the lateral root mass density was then calculated.

2.3.4. Yield and oil production

At harvest, all the plants in an area of 1 m^2 at the center of each plot were selected to determine yield components, including branch number per plant, pod number per plant, seed number per pod and 1000-seed weight. The final rapeseed yield was determined after plants were sun-dried and threshed. Seed oil content was determined by near-infrared reflectance spectroscopy (NIR System 5000, Foss, Denmark). Oil production was calculated by multiplying seed oil content by seed yield.

2.3.5. Evapotranspiration and water use efficiency

Before sowing and after harvesting, the soil was sampled to a depth of 2.0 m at 0.1-m intervals using a portable auger (about 7 cm in diameter) at the middle of two adjacent plants in the same row. The gravimetric water content of the soil samples at each depth was calculated from their oven-dried weights (dried at 105 °C). The soil water storage (SWS) in the soil profile (0 to 2.0 m) before sowing and after harvesting throughout each growing season was then calculated by the following formula:

$$SWS = \Sigma(GWC_i \times \gamma_i \times SD_i) \quad (1)$$

where GWC_i, γ_i, and SD_i are soil gravimetric water content (%), soil dry bulk density (g cm^{-3}), and soil depth (mm) in each soil layer, respectively. i = 1, 2, 3, …, 19, 20.

Evapotranspiration (ET, mm) was determined using the soil water balance equation:

$$ET = I + P - R - D + SWS_b - SWS_a \quad (2)$$

where I is irrigation amount (mm); P is precipitation (mm); R is runoff (mm); D is deep drainage to a boundary depth of 2.0 m, and SWS_b and SWS_a are soil water storage (mm) in the soil profile (0–2.0 m) before sowing and after harvesting, respectively, for each growing season. Runoff and deep drainage were considered negligible (zero) because no heavy rain and un-planned irrigation occurred throughout the rapeseed growing seasons. Therefore, the calculation of ET could be simplified as:

$$ET = I + P + SWS_b - SWS_a \quad (3)$$

Water use efficiency (WUE, kg ha^{-1} mm^{-1}) was defined using the following formula:

$$WUE = Y/ET \quad (4)$$

where Y is winter rapeseed yield (kg ha^{-1}) and ET is evapotranspiration of winter rapeseed (mm).

2.4. Data analysis

All data are presented as the mean value of the three replicates. SPSS 18.0 was used to conduct analysis of variance, and the significance of differences between the treatments was determined by the least significant differences test at $P < 0.05$ level. Figures were created by Origin 8.0.

3. Results

3.1. Meteorological condition

The annual, monthly and seasonal distribution patterns of precipitation differed among the three study years and from the long-term average (Fig. 2a). In 2014–2015, rainfall in the early period (from September to November) was lower, and in the late period (from March to May) was much higher than the long-term average; however, the annual precipitation in 2014–2015 was 270.5 mm, which was almost equal to that of the long-term average (278.3 mm). Thus, precipitation pattern of 2014–2015 was considered to be “normal”. In 2015–2016, the precipitation was similar to the long-term average in the early period, and was much lower than the long-term average in the late period; annual rainfall was about 65 mm lower than the long-term average. Therefore, 2015–2016 was considered as a “dry” year. In 2016–2017, the precipitation patterns in the early and late periods were both higher than the long-term averages of the same periods, and the annual rainfall was about 100 mm more than the long-term average. Hence, 2016–2017 was declared as a “wet” year.

Monthly mean air temperatures during the growing seasons of winter oilseed rape generally exhibited the same trend across 2014–2015, 2015–2016, and 2016–2017 in comparison to the long-term (from 2000 to 2013) average, except that the air temperature in January was higher for 2014–2015 and 2016–2017 than the long-term average (Fig. 2b).

3.2. Shoot dry matter

Over the three growing seasons, RFFM0 consistently gained significantly higher shoot dry matter than FP0 and FP1 (Table 3), with greater mean differences by 33.3% and 25.3%, respectively. In 2014–2015 (normal rainfall year) and 2016–2017 (wet year), shoot dry matter in RFFM0 was also remarkably higher than that in FP2, but did not differ significantly from that in FP3. In 2015–2016, the dry year, shoot dry matter in RFFM0 was almost equal to that in FP2, and dramatically lower than that in FP3. While compared to RFFM1, shoot dry matter in RFFM0 was noticeably lower in 2014–2015 and 2015–2016, but no differences were observed in 2016–2017.

3.3. Nutrient uptake

As shown in Table 4, nitrogen (N), phosphorus (P) and potassium (K) uptake consistently increased with the increase of irrigation frequency and amount. FP2 and FP3 significantly increased N, P and K uptake by 46.0% and 24.9%, 47.3% and 21.2%, and 40.9% and 21.2% compared to FP0, respectively. In 2014–2015, the normal rainfall year, N, P and K uptake in RFFM0 were significantly higher than those in FP2, significantly lower than those in RFFM1, and did not differ significantly from those in FP3. In 2015–2016, the dry year, RFFM0 obtained markedly lower N, P and K uptake amounts compared to FP3 and RFFM1; and there was no significant difference between RFFM0 and FP2. In 2016–2017, the wet year, N, P and K uptake rates were remarkably higher in RFFM0 than in FP2; no remarkable differences were observed among FP3, RFFM0 and RFFM1.

3.4. Root morphology

3.4.1. Taproot characteristics

The FP0 group consistently had the longest taproot that was, on average, 7.8%, 14.8%, 14.4% and 19.3% significantly longer than the taproots of FP2, FP3, RFFM0 and RFFM1, respectively (Table 5). Taproot length in RFFM0 did not differ markedly from FP3 and RFFM1, but was significantly shorter than that in FP2 in 2014–2015 (normal rainfall year) and 2016–2017 (wet year). However, in 2015–2016, taproot length of RFFM0 was significantly longer than those in FP3 and RFFM1, but no significant differences were found between RFFM0 and FP2.

Taproot diameter of RFFM0 was consistently thicker than that of FP0 and FP1 by 22.8% and 19.7%, respectively (Table 5). In 2014–2015, the normal rainfall year, taproot diameter of RFFM0 did not differ markedly from that of FP3 and RFFM1, but was remarkably greater than that of FP2. Furthermore, the taproot diameter of RFFM1 was significantly thicker than the diameter of FP3. In 2015–2016, the dry year, taproot diameter of RFFM0 did not differ significantly from that of FP2, but was markedly thinner than that of RFFM1 and FP3. In 2016–2017, the wet year, taproot diameters did not differ significantly among FP3, RFFM0 and RFFM1; however, they were markedly greater than the diameter of FP2.

Generally, taproot dry weight significantly increased as the

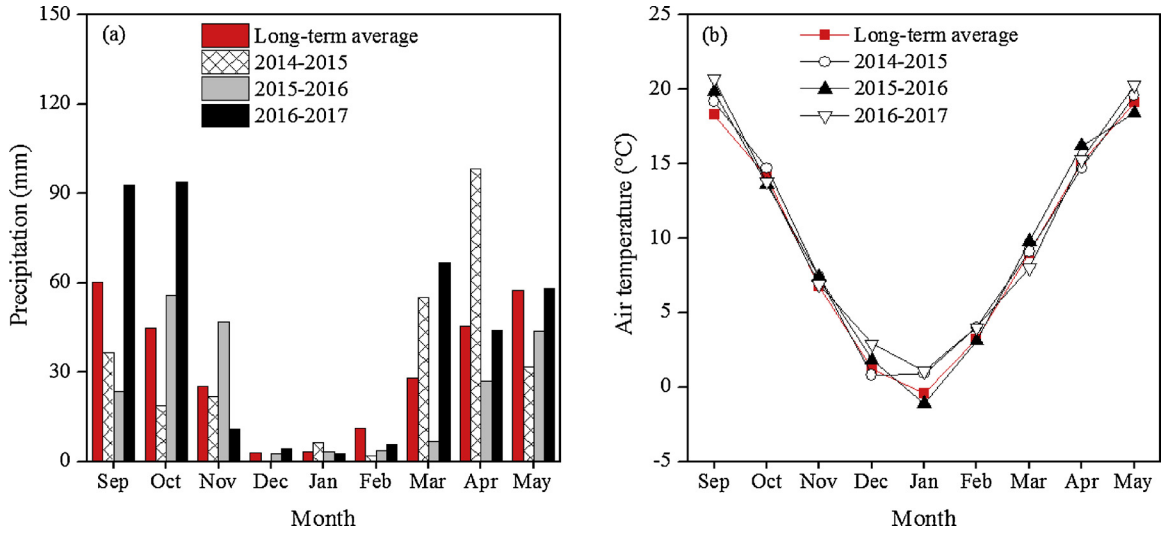

Fig. 2. The monthly total precipitation (a) and monthly mean air temperature (b) during the winter oilseed rape growing seasons in 2014–2015, 2015–2016, 2016–2017, and the long-term (from 2000 to 2013) average at the experimental site.

Table 3
Shoot dry matter (kg ha^{-1}) at the harvest stage of winter oilseed rape grown under different combinations of planting pattern and irrigation treatments for three growing seasons.

Treatment	2014-2015	2015-2016	2016-2017
FP0	8147 ± 152 e	6578 ± 208 d	7529 ± 230 c
FP1	8620 ± 191 d	7093 ± 302 c	7955 ± 256 c
FP2	9790 ± 260 c	8355 ± 379 b	9261 ± 365 b
FP3	11404 ± 394 ab	9374 ± 456 a	10428 ± 353 a
RFFM0	11028 ± 267 b	8316 ± 506 b	10311 ± 328 a
RFFM1	11551 ± 237 a	9481 ± 512 a	10660 ± 461 a

Data are mean ± standard error of the three replicates. Different lowercase letters within a column indicate significant differences among treatments within a season at $P < 0.05$ level. FP and RFFM denote flat planting without film mulching and ridge-furrow full film mulching planting patterns, respectively. The digit '0' represents no irrigation; the digit '1' represents a one-time irrigation of 30 mm at the over-wintering stage for FP and 45 mm at the flowering stage for RFFM; the digit '2' represents two times of irrigation of 30 and 60 mm of water at the over-wintering and stem elongation stages, respectively; the digit '3' represents three periods of irrigation of 30, 60 and 60 mm of water at the over-wintering, stem elongation and flowering stages, respectively.

irrigation times and amounts increased (Table 5). In 2014–2015 and 2016–2017, significant differences were not observed among taproot dry weights in FP3, RFFM0 and RFFM1 treatments, but those weights were significantly higher than weights in FP0, FP1 and FP2 treatments. In 2015–2016, taproot dry weight of RFFM0 was significantly lower than the dry weight of FP3 and RFFM1, almost equal to the dry weight of FP2, and significantly higher than the dry weights of FP0 and FP1.

3.4.2. *Lateral-root distribution*

Lateral-root mass density sharply decreased with the increase of soil depth (Fig. 3). On average, lateral-root mass density in the 0–10 cm soil layer was 2.8 and 8.5 times greater than that of the 10–20 and 20–30 cm soil layers, respectively. The highest lateral-root mass density consistently occurred in RFFM1 in the 0–10 and 10–20 cm soil layers, and in FP0 in the 20–30 cm soil layer over the three growing seasons.

In the 0–10 and 10–20 cm soil layers, RFFM0 consistently obtained significantly higher lateral-root mass density than that of FP0 and FP1 across the three seasons. In 2014–2015, lateral-root mass density in RFFM0 was significantly higher than that in FP2, but did not differ markedly from that in FP3 and RFFM1. In 2015–2016, RFFM0 gained similar lateral-root mass density to FP2, and markedly lower lateral-root mass density than FP3 and RFFM1. In 2016–2017, lateral-root mass density did not differ significantly between RFFM0 and FP3, and was significantly higher in RFFM0 than FP2; in addition, lateral-root mass density in RFFM0 was markedly lower than that in RFFM1 in the 0–10 cm soil layer, and no significant differences were observed between RFFM0 and RFFM1 in the 10–20 cm soil layer.

In the 20–30 cm soil layer, there were no marked differences among

Table 4
Nutrient uptake at the harvest stage of winter oilseed rape grown under different combinations of planting pattern and irrigation treatments for three growing seasons.

Treatment	Nitrogen uptake (kg ha^{-1})			Phosphorus uptake (kg ha^{-1})			Potassium uptake (kg ha^{-1})		
	2014-2015	2015-2016	2016-2017	2014-2015	2015-2016	2016-2017	2014-2015	2015-2016	2016-2017
FP0	80.8 ± 7.2 de	68.6 ± 3.7 d	72.3 ± 6.1 cd	34.1 ± 3.4 d	29.4 ± 2.8 c	31.5 ± 3.3 c	94.6 ± 5.7 d	81.8 ± 2.9 d	86.3 ± 4.6 c
FP1	85.1 ± 4.1 d	74.7 ± 4.2 c	77.2 ± 7.5 c	36.4 ± 1.7 d	31.9 ± 4.2 bc	33.6 ± 2.8 c	99.7 ± 4.1 d	89.2 ± 4.7 c	92.9 ± 6.9 c
FP2	95.3 ± 5.8 c	89.1 ± 4.4 b	92.6 ± 5.1 b	40.8 ± 2.7 c	35.6 ± 3.3 b	38.7 ± 2.1 b	108.8 ± 5.0 c	102.5 ± 4.5 b	107.0 ± 6.8 b
FP3	112.6 ± 6.9 ab	102.9 ± 7.0 a	108.1 ± 6.6 a	48.9 ± 3.2 ab	43.9 ± 2.6 a	47.1 ± 5.1 a	126.0 ± 5.8 ab	118.3 ± 4.8 a	125.8 ± 8.0 a
RFFM0	109.3 ± 4.4 b	85.3 ± 3.1 b	104.0 ± 6.1 a	46.1 ± 2.5 b	38.7 ± 2.5 b	44.2 ± 3.2 a	121.6 ± 4.1 b	105.7 ± 5.4 b	118.4 ± 4.3 a
RFFM1	118.7 ± 4.7 a	105.6 ± 5.1 a	110.9 ± 9.2 a	51.8 ± 3.0 a	45.1 ± 3.8 a	48.3 ± 5.8 a	131.5 ± 5.7 a	120.5 ± 6.0 a	127.0 ± 11.4 a

Data are mean ± standard error of the three replicates. Different lowercase letters within a column indicate significant differences among treatments within a season at $P < 0.05$ level. FP and RFFM denote flat planting without film mulching and ridge-furrow full film mulching planting patterns, respectively. The digit '0' represents no irrigation; the digit '1' represents a one-time irrigation of 30 mm at the over-wintering stage for FP and 45 mm at the flowering stage for RFFM; the digit '2' represents two times of irrigation of 30 and 60 mm of water at the over-wintering and stem elongation stages, respectively; the digit '3' represents three periods of irrigation of 30, 60 and 60 mm of water at the over-wintering, stem elongation and flowering stages, respectively.

Table 5
Taproot growth parameters of winter oilseed rape cultivated in different combinations of planting pattern and irrigation treatments for three growing seasons.

Growing season	Treatment	Taproot length (cm)	Taproot diameter (mm)	Taproot dry weight (g plant^{-1})
2014-2015	FP0	20.5 ± 0.7 a	11.7 ± 0.4 d	4.5 ± 0.4 c
	FP1	20.3 ± 0.6 a	11.8 ± 0.3 d	4.6 ± 0.3 c
	FP2	19.2 ± 0.4 b	12.6 ± 0.4 c	5.3 ± 0.3 b
	FP3	17.9 ± 0.4 c	14.5 ± 0.3 b	6.4 ± 0.7 a
	RFFM0	17.6 ± 0.4 cd	15.0 ± 0.5 ab	6.6 ± 0.4 a
	RFFM1	17.1 ± 0.3 d	15.4 ± 0.5 a	6.9 ± 0.6 a
2015-2016	FP0	21.1 ± 0.7 a	11.1 ± 0.4 d	4.2 ± 0.3 d
	FP1	20.7 ± 0.5 a	11.5 ± 0.7 cd	4.3 ± 0.3 cd
	FP2	19.7 ± 0.4 b	12.3 ± 0.5 bc	4.9 ± 0.4 bc
	FP3	18.5 ± 0.5 c	13.8 ± 0.8 a	5.8 ± 0.4 a
	RFFM0	19.4 ± 0.3 b	12.6 ± 0.3 b	5.0 ± 0.3 b
	RFFM1	17.9 ± 0.4 c	14.0 ± 0.5 a	5.7 ± 0.3 a
2016-2017	FP0	20.3 ± 0.8 a	12.3 ± 0.4 c	4.8 ± 0.7 c
	FP1	19.8 ± 0.6 a	12.7 ± 0.6 c	5.0 ± 0.5 c
	FP2	18.5 ± 0.5 b	14.1 ± 0.5 b	6.0 ± 0.4 b
	FP3	17.5 ± 0.4 c	15.0 ± 0.3 a	6.9 ± 0.4 a
	RFFM0	17.1 ± 0.4 c	15.5 ± 0.4 a	7.2 ± 0.5 a
	RFFM1	16.9 ± 0.3 c	15.7 ± 0.5 a	7.4 ± 0.7 a

Data are mean ± standard error of the three replicates. Different lowercase letters within a column indicate significant differences among treatments within a season at $P < 0.05$ level. FP and RFFM denote flat planting without film mulching and ridge-furrow full film mulching planting patterns, respectively. The digit '0' represents no irrigation; the digit '1' represents a one-time irrigation of 30 mm at the over-wintering stage for FP and 45 mm at the flowering stage for RFFM; the digit '2' represents two times of irrigation of 30 and 60 mm of water at the over-wintering and stem elongation stages, respectively; the digit '3' represents three periods of irrigation of 30, 60 and 60 mm of water at the over-wintering, stem elongation and flowering stages, respectively.

lateral-root mass density in FP2, FP3, RFFM0 and RFFM1 across the three seasons. Lateral-root mass density in RFFM0 was significantly lower than that in FP1 in 2014–2015, and significantly lower than that in FP0 over the three seasons.

3.5. Yield components and yield

As expected, winter rapeseed yield and its related components were significantly affected by planting patterns and irrigation levels across the three growing seasons (Table 6). Compared to FP0 and FP1, RFFM0 significantly improved branch number per plant, pod number per plant, seed number per pod, seed number per m^2 and 1000-seed weight over the three growing seasons. The five aforementioned yield components of RFFM0 did not differ markedly from those of FP2 except for seed numbers per m^2 in 2014–2015, and pod numbers per plant, seed numbers per pod and per m^2 in 2016–2017. When compared to FP3, RFFM0 obtained almost the same values for yield components in 2014–2015 (normal rainfall year) and 2016–2017 (wet year); however, pod number per plant and seed number per m^2 were significantly higher in FP3 than in RFFM0 in 2015–2016 (dry year). Furthermore, between the two RFFM treatments, pod number per plant and seed number per m^2 in RFFM1 were significantly higher than the numbers in RFFM0 in 2014–2015 and 2015–2016.

Among the four FP treatments, yield significantly increased as the irrigation frequency and amount increased, and average yield was markedly enhanced by 42.4%, 30.8% and 12.9% in FP3 compared to FP0, FP1 and FP2, respectively (Table 6). Averaged across the three seasons, yield in RFFM0 was 37.3% and 26.1% significantly higher than yield in FP0 and FP1, respectively. Yield in RFFM0 was significantly greater in 2014–2015 (normal rainfall year) and 2016–2017 (wet year), but was nearly the same in 2015–2016 (dry year) compared to yield in FP2. Compared to yield in FP3 in 2014–2015 (normal rainfall year) and 2016–2017 (wet year), yield in RFFM0 was nearly equal, while a significant reduction was observed in 2015–2016 (dry year). When comparing the yield between the two RFFM treatments, RFFM1 significantly improved the yield of winter oilseed rape in 2014–2015 and 2015–2016 in comparison to RFFM0; while no significant difference was observed in 2016–2017.

3.6. Oil content and oil production

Oil content is a very important indicator for rapeseed. RFFM1 consistently obtained the highest oil content, and no significant differences were found among RFFM1, RFFM0 and FP3 across the three growing seasons (Fig. 4). In 2014–2015 and 2016–2017, the oil content in FP2 was markedly lower than that in RFFM0, but did not show a significant difference in 2015–2016. The oil content in FP0 was consistently the lowest and significantly lower than other treatments except for FP1 over the three growing seasons.

Oil production was consistently the highest in RFFM1

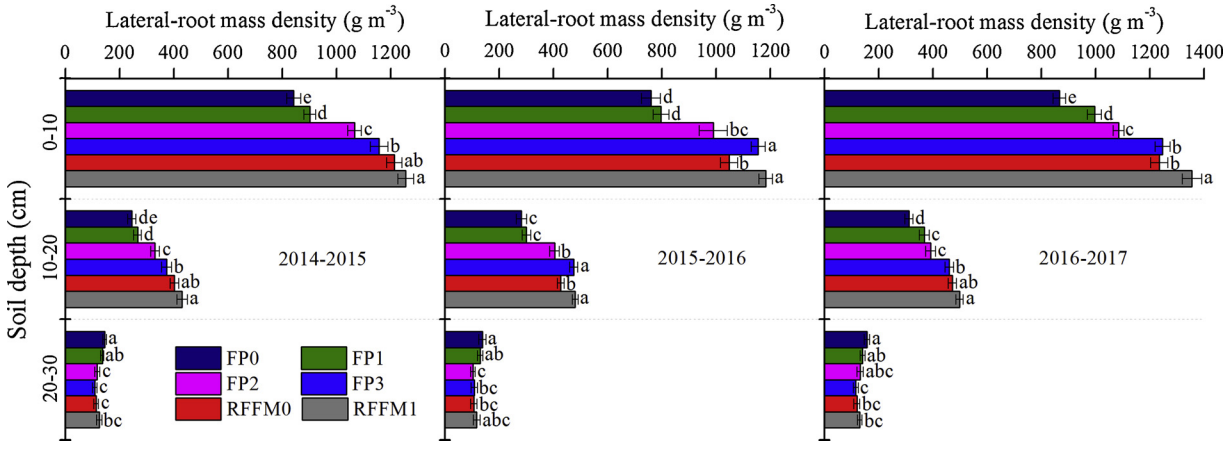

Fig. 3. Distribution of lateral-root mass density at harvest stage of winter oilseed rape cultivated under different treatments across the three growing seasons. Bars represent the standard error. Within each growth stage for each growing season, bars with different lowercase letters indicate significant differences among treatments at $P < 0.05$. FP and RFFM denote flat planting without film mulching and ridge-furrow full film mulching planting patterns, respectively. The digit '0' represents no irrigation; the digit '1' represents a one-time irrigation of 30 mm at the over-wintering stage for FP and 45 mm at the flowering stage for RFFM; the digit '2' represents two times of irrigation of 30 and 60 mm of water at the over-wintering and stem elongation stages, respectively; the digit '3' represents three periods of irrigation of 30, 60 and 60 mm of water at the over-wintering, stem elongation and flowering stages, respectively.

Table 6
Yield components and yield of winter oilseed rape cultivated under different treatments across the three growing seasons.

Treatment	Branch numbers *per* plant	Pod numbers *per* plant	Seed numbers *per* pod	Seed numbers *per* m^2 ($\times 10^3$)	1000-seed weight (g)	Yield (kg ha^{-1})
2014-2015						
FP0	11.0 ± 0.5 c	315 ± 28 d	23.4 ± 0.4 b	88.5 ± 4.5 de	3.41 ± 0.07 b	2503 ± 104 e
FP1	11.3 ± 0.4 c	336 ± 26 cd	23.9 ± 0.7 b	96.4 ± 4.2 d	3.42 ± 0.14 b	2709 ± 60 d
FP2	12.9 ± 0.6 b	384 ± 29 c	25.3 ± 0.5 ab	116.6 ± 6.0 c	3.51 ± 0.11 ab	3098 ± 131 c
FP3	13.6 ± 0.5 ab	433 ± 19 ab	26.1 ± 0.7 a	135.6 ± 11.7 ab	3.64 ± 0.06 a	3497 ± 82 ab
RFFM0	13.2 ± 0.7 ab	406 ± 21 bc	26.3 ± 1.0 a	128.1 ± 5.0 b	3.62 ± 0.05 a	3393 ± 92 b
RFFM1	14.1 ± 0.6 a	448 ± 20 a	26.6 ± 0.6 a	143.0 ± 4.6 a	3.68 ± 0.10 a	3562 ± 73 a
2015-2016						
FP0	11.1 ± 0.5 c	286 ± 29 cd	22.6 ± 1.0 c	77.6 ± 5.5 cd	3.31 ± 0.06 c	2010 ± 71 d
FP1	11.3 ± 0.5 c	308 ± 24 c	22.9 ± 0.6 c	84.6 ± 6.0 c	3.33 ± 0.05 c	2236 ± 139 c
FP2	12.6 ± 0.7 ab	351 ± 17 b	24.2 ± 0.7 b	101.9 ± 7.8 b	3.44 ± 0.09 abc	2697 ± 208 b
FP3	13.2 ± 0.8 a	403 ± 21 a	25.4 ± 0.5 a	122.8 ± 9.6 a	3.52 ± 0.11 a	3059 ± 151 a
RFFM0	12.5 ± 0.8 ab	360 ± 20 b	24.3 ± 0.8 ab	105.0 ± 7.5 b	3.46 ± 0.07 ab	2766 ± 74 b
RFFM1	13.5 ± 0.7 a	413 ± 32 a	25.1 ± 0.9 ab	124.4 ± 4.6 a	3.54 ± 0.07 a	3175 ± 118 a
2016-2017						
FP0	10.2 ± 0.3 c	298 ± 30 cd	22.9 ± 0.5 c	81.9 ± 4.6 d	3.36 ± 0.08 b	2360 ± 71 d
FP1	10.6 ± 0.4 c	321 ± 29 c	23.3 ± 0.5 c	89.8 ± 3.2 c	3.39 ± 0.05 b	2539 ± 97 c
FP2	12.8 ± 0.7 b	373 ± 22 b	24.9 ± 0.8 b	111.5 ± 8.2 b	3.53 ± 0.13 ab	2876 ± 192 b
FP3	13.7 ± 0.7 ab	419 ± 23 a	26.3 ± 1.3 ab	132.2 ± 9.0 a	3.61 ± 0.07 a	3234 ± 141 a
RFFM0	13.9 ± 0.6 ab	415 ± 20 a	26.7 ± 0.5 a	133.0 ± 9.9 a	3.64 ± 0.12 a	3281 ± 159 a
RFFM1	14.2 ± 0.6 a	425 ± 30 a	26.9 ± 0.7 a	137.2 ± 8.7 a	3.67 ± 0.08 a	3362 ± 118 a

Data are mean ± standard error of the three replicates. Different lowercase letters within a column indicate significant differences among treatments within a season at $P < 0.05$ level. FP and RFFM denote flat planting without film mulching and ridge-furrow full film mulching planting patterns, respectively. The digit '0' represents no irrigation; the digit '1' represents a one-time irrigation of 30 mm at the over-wintering stage for FP and 45 mm at the flowering stage for RFFM; the digit '2' represents two times of irrigation of 30 and 60 mm of water at the over-wintering and stem elongation stages, respectively; the digit '3' represents three periods of irrigation of 30, 60 and 60 mm of water at the over-wintering, stem elongation and flowering stages, respectively.

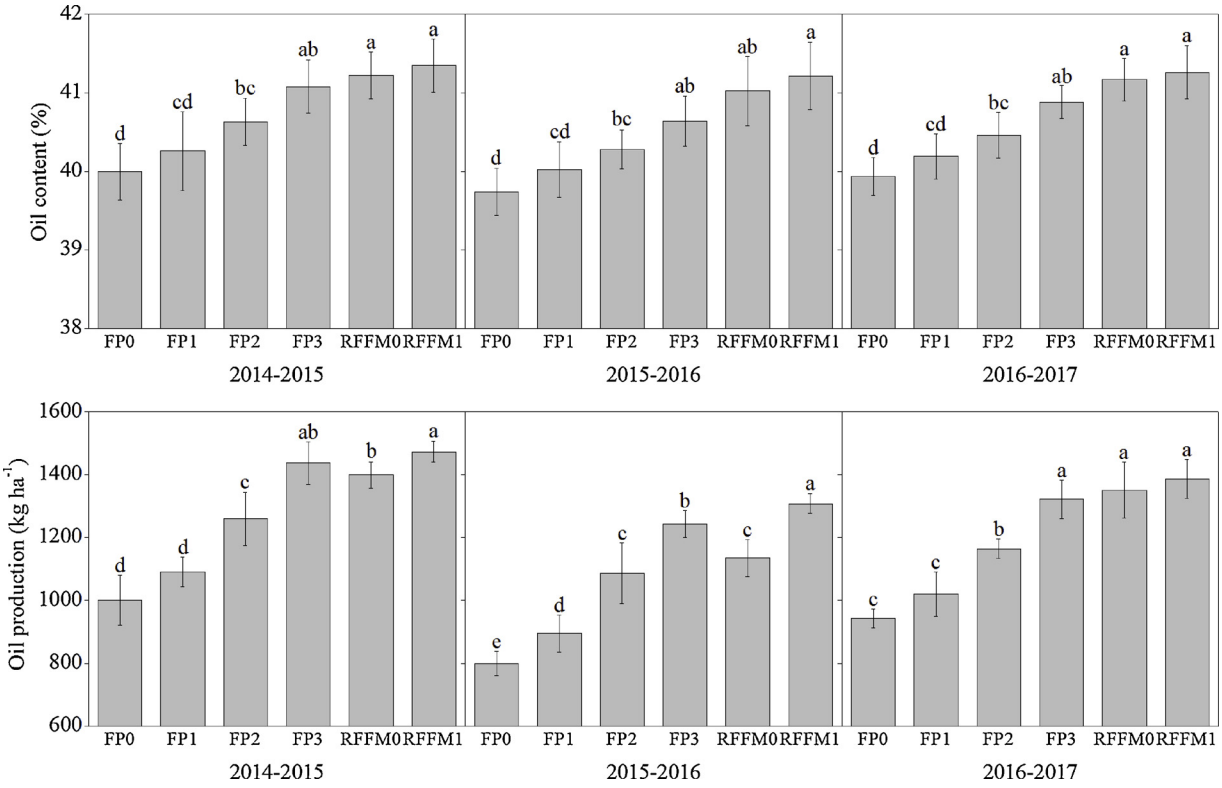

Fig. 4. Oil contents and oil production of winter oilseed rape cultivated under different treatments across the three growing seasons. Bars represent the standard error. Within each growth stage for each growing season, bars with different lowercase letters indicate significant differences among treatments at $P < 0.05$. FP and RFFM denote flat planting without film mulching and ridge-furrow full film mulching planting patterns, respectively. The digit '0' represents no irrigation; the digit '1' represents a one-time irrigation of 30 mm at the over-wintering stage for FP and 45 mm at the flowering stage for RFFM; the digit '2' represents two times of irrigation of 30 and 60 mm of water at the over-wintering and stem elongation stages, respectively; the digit '3' represents three periods of irrigation of 30, 60 and 60 mm of water at the over-wintering, stem elongation and flowering stages, respectively.

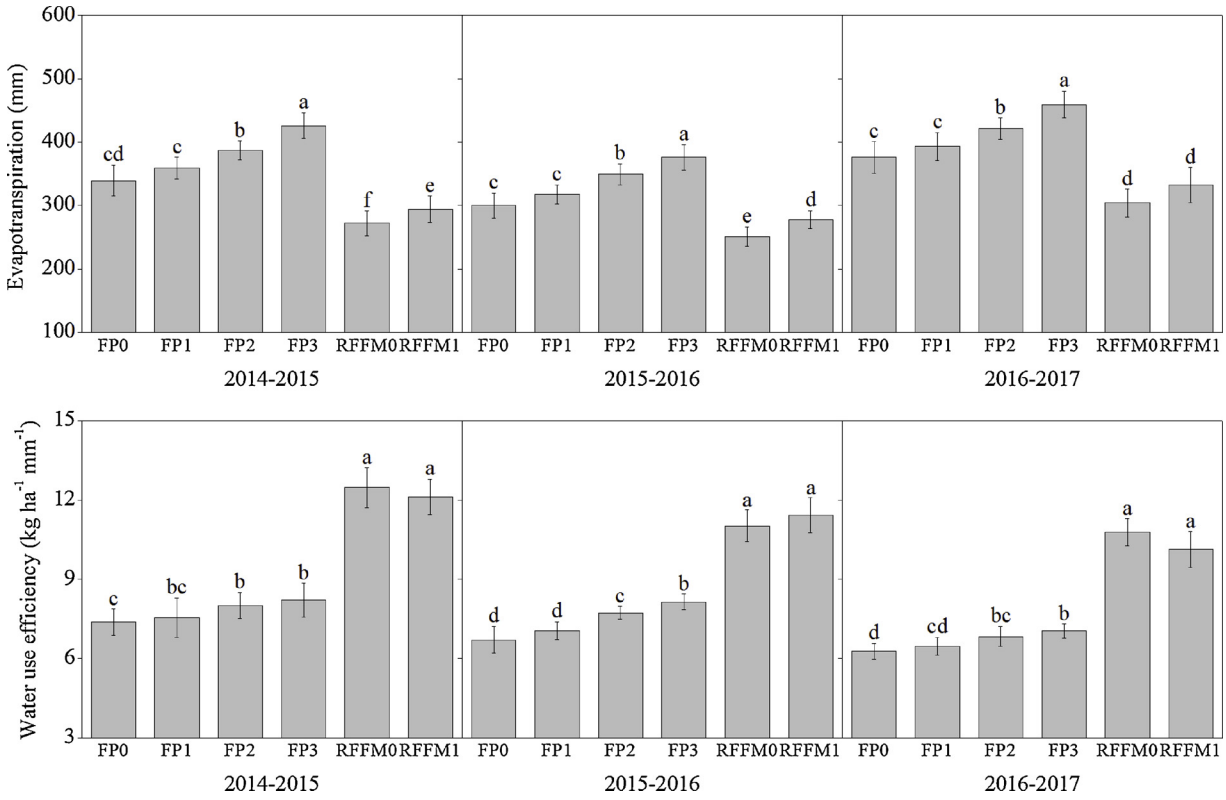

Fig. 5. Evapotranspiration and water use efficiency of winter oilseed rape cultivated under different treatments across the three growing seasons. Bars represent the standard error. Within each growth stage for each growing season, bars with different lowercase letters indicate significant differences among treatments at $P < 0.05$. FP and RFFM denote flat planting without film mulching and ridge-furrow full film mulching planting patterns, respectively. The digit '0′ represents no irrigation; the digit '1′ represents a one-time irrigation of 30 mm at the over-wintering stage for FP and 45 mm at the flowering stage for RFFM; the digit '2′ represents two times of irrigation of 30 and 60 mm of water at the over-wintering and stem elongation stages, respectively; the digit '3′ represents three periods of irrigation of 30, 60 and 60 mm of water at the over-wintering, stem elongation and flowering stages, respectively.

(1308–1473 kg ha^{-1}) and the lowest in FP0 (799–1001 kg ha^{-1}) across the three growing seasons (Fig. 4). In addition, oil production in FP3, RFFM0 and RFFM1 was also consistently higher than that in FP0, FP1 and FP2, except that no significant differences were observed between FP2 and RFFM0 in 2015–2016. Moreover, clear differences were also observed in all three different rainfall years. In 2014–2015, oil production in RFFM0 was 5.0% (74.3 kg ha^{-1}) significantly lower than oil production in RFFM1, but did not differ markedly compared to that in FP3. In 2015–2016, oil production in FP3 was 9.6% (108.6 kg ha^{-1}) significantly higher than that in RFFM0 and 5.0% (65.2 kg ha^{-1}) significantly lower than that in RFFM1. In 2016–2017, no differences were observed among FP3, RFFM0 and RFFM1.

3.7. ET and WUE

Over the three growing seasons, plants in the two RFFM treatments consumed less water and had higher WUE compared to that in the four FP treatments (Fig. 5). Regardless of irrigation frequency and amount, ET in RFFM was 25.1% (94.8 mm), 21.2% (71.0 mm) and 22.9% (94.3 mm) lower, and WUE in RFFM was 57.9% (4.51 kg ha^{-1} mm^{-1}), 51.5% (3.82 kg ha^{-1} mm^{-1}) and 57.2% (3.81 kg ha^{-1} mm^{-1}) higher than that in FP in the 2014–2015, 2015–2016 and 2016–2017 growing seasons, respectively. Moreover, RFFM0 significantly decreased ET by 18.5% (62.7 mm) and improved WUE by 68.4% (4.64 kg ha^{-1} mm^{-1}) on average compared to FP0 across the three growing seasons.

As shown in Fig. 5, ET significantly increased with the increase of irrigation frequency and amount, while WUE did not drastically improve. Among the four FP treatments, mean ET and WUE in FP3 were greater by 24.2% and 14.9%, 18.0% and 11.1%, 9.0% and 3.7% in comparison to those of FP0, FP1 and FP2, respectively. WUE did not differ significantly between the two RFFM treatments over the three growing seasons, though RFFM1 markedly increased ET in 2014–2015 and 2015–2016 compared to RFFM0.

4. Discussion

Climate change may exacerbate major threats, such as water scarcity and unbalanced rainfall distribution, to agricultural sustainability. Ridge-furrow full film mulching, particularly in combination with supplemental irrigation at critical growth stages of crops, may be a promising adaptive management strategy for dryland agriculture, especially in light of the potential negative impacts of climate change.

4.1. Ridge-furrow full film mulching (RFFM) planting pattern

Previous studies have demonstrated that film mulching, particularly the ridge-furrow planting pattern with full-film mulching (RFFM), can greatly improve soil hydro-thermal conditions for dryland farming in arid and semiarid regions (Mo et al., 2017; Qin et al., 2014; Zhang et al., 2017). In the present experiment, soil moisture in RFFM0 was 1.5–5.9% higher than soil moisture in FP0 during whole growing season, and daily mean soil temperature in RFFM0 was 1.0–4.2 °C higher than that in FP0 at the early growth stages (before flowering) over the three growing seasons. The warmer and wetter soil environment likely promoted growth of strong root systems in the RFFM0 crop, including robust taproots and well-distributed and well-developed lateral roots (Table 5 and Fig. 3). It is well known that plants with strong root systems can absorb more water and nutrients in the soil, which results in quicker plant growth and greater biomass (Li et al., 2015) and is supported by data obtained in this study; RFFM0 had significantly

higher shoot dry matter and absorbed more N, P and K nutrients in comparison to those of FP0 (Tables 3 and 4).

Previous studies have demonstrated that RFFM is an effective method to significantly improve yield and WUE in wheat (Zhang et al., 2007), maize (Mo et al., 2017), potato (Qin et al., 2014), oilseed rape (Gu et al., 2018), and proso millet (Zhang et al., 2017) in arid and semiarid regions. Compared to FP0, RFFM0 markedly increased branch and pod numbers *per* plant, seed numbers *per* pod and *per* m^2, and 1000-seed weight over the three growing seasons in this study. Furthermore, RFFM0 improved rapeseed yield and WUE by 35.6–39.0% and 64.5–72.0%, respectively. Improvements by the RFFM treatment may be due to its more effective use of light precipitation by retaining more soil water and decreasing soil evaporation, which increases crop transpiration, enhances biomass accumulation and thus improves grain yield (Gu et al., 2017). Evapotranspiration is the sum of soil evaporation (E) and plant transpiration (T). The presence of plastic sheets over the soil surface may help conserve water in the soil by inhibiting E (Bond and Willis, 1969), especially at early growth periods when the crop canopy is small. In this study, ET in RFFM0 at the seedling stage of winter oilseed rape was approximate 40.4–81.3 mm lower than that in FP0 (data not shown). The plastic film in RFFM0 likely intercepted solar radiation and reduced wind speed close to the soil surface, and thus decreased E (Jalota and Prihar, 1990). Moreover, the resulting larger canopies of crops in the RFFM0 treatment created more shade over the soil surface which also likely reduces E (Li et al., 2015; Gu et al., 2018). The water saved from potential loss by E in the early growth period could then be used in T in the late growth period to increase water productivity (Li et al., 2008). In our study, from the stem elongation to maturity stage, RFFM0 increased ET by about 15.2–39.8 mm more than ET in FP0. Finally, RFFM0 significantly decreased ET by about 50–70 mm compared to ET in FP0 during whole growing season of winter oilseed rape. In addition, results of the present study showed that RFFM0 markedly enhanced oil content and thus oil production compared to FP0. Previous researchers, such as Sun et al. (2006) and Gu et al. (2017) also observed similar results.

4.2. Adaptive management for dryland agriculture

Limited capacity to adapt to climate change is a great challenge for dryland agriculture. Adaptive management for farming systems is expected to increase resilience of agroecosystems and reduce variability in yield, and eventually increase a system's capacity to respond to climate change (Parry et al., 2005; Thornton et al., 2011; Mo et al., 2017). Thus, adaptive management is an important approach to improve agricultural production.

Irrigation frequency and amount are two critical factors for improving crop yield and WUE for dryland agriculture with limited water supply (Wang, 2017). In many agricultural regions in China, winter crops are irrigated at their most water-demanding growth stages, overwintering, jointing and flowering, to ensure high WUE and high yield in properly watered crops. In the present study, irrigation of winter oilseed rape of FP treatments occurred at these three critical stages, and not surprisingly, shoot and root biomass, nutrient uptake, yield, oil content, oil production and WUE improved with the increase of irrigation frequency and amount. The results of previous studies were in complete agreement with results of this study (Payero et al., 2008; Zhou et al., 2017; Wang, 2017). Moreover, ET substantially increased as the irrigation frequency and amount increased. ET in FP1, FP2 and FP3 were about 20, 50 and 80 mm higher than ET in FP0 (Fig. 5) at expense of consuming 30, 90 and 150 mm more irrigation water, respectively.

Considering that the availability of water for irrigation is becoming scarce due to less rainfall as well as an increasing demand of water for domestic, industrial, municipal and other activities (Hamzei, 2011), traditional flat planting pattern would be an inappropriate method to use in the changing climate for dryland farming. Thus a water-saving cultivation pattern, such as ridge-furrow film mulching, must be adopted for dryland agriculture. Ridge-furrow film mulching, especially ridge-furrow with full film mulching (RFFM) is an easy and effective method that can increase soil moisture and temperature, and has great potential to save water and improve crop production in arid and semiarid areas (Gu et al., 2016; Mo et al., 2017; Zhang et al., 2017). In the present study, both RFFM0 and RFFM1 significantly decreased ET and improved WUE of winter oilseed rape compared to those of the FP treatments in the dry year (2015–2016), normal rainfall year (2014–2015) and wet year (2016–2017) (Fig. 5). However, rapeseed yield and oil production varied markedly between RFFM and FP treatments in different rainfall years. Rapeseed yield and oil production in RFFM0 were nearly equal to those of FP2 and significantly lower than those of FP3 in the dry year (2015–2016). Furthermore, they were equivalent to FP3 in the normal rainfall (2014–2015) and wet years (2016–2017) (Table 6 and Fig. 4). Furthermore, when irrigated with 45 mm of water at the flowering stage in the RFFM treatment, rapeseed yield and oil production significantly increased compared to those in RFFM0 in the normal rainfall (2014–2015) and dry years (2015–2016), and were significantly higher than those of FP3 in the dry year (2015–2016). This suggests that the RFFM planting pattern, indeed, improved crop yield for dryland agriculture, but the effect for increasing yield is also dependent upon the amount and distribution of precipitation during the crop growth season (Ren et al., 2016). Therefore, supplemental irrigation with RFFM is necessary in certain rainfall years, especially in dry years. In normal and dry years, we determined that 45 mm of irrigation water delivered at the flowering stage in combination with RFFM is sufficient, as long as irrigation water is available. Moreover, we determined that RFFM without supplemental irrigation could successfully produce high rapeseed yield and oil production in each of the three growing seasons of different rainfall types, and thus we can recommend it as an adaptive management strategy for dryland agriculture.

In the present study, we also found that rapeseed yield, oil production and WUE were all higher in 2014–2015 (normal rainfall year) than in 2015–2016 (dry year) and 2016–2017 (wet year). More rainfall occurred during the flowering stage in 2014–2015 which may have caused these results. This indicates that the timing of application of supplemental irrigation, in this case at the flowering stage, can benefit dryland winter oilseed rape in water-scarce regions.

5. Conclusions

The present study demonstrated that ridge-furrow full film mulching (RFFM) had positive effects on improving yield and saving water for dryland cultivation of winter oilseed rape. However, the yield-increasing and water-saving effects of RFFM differed in comparison to traditional flat planting (FP) with irrigation in the three levels of rainfall years. The RFFM treatment achieved commensurate rapeseed yield and oil production as FP with supplemental irrigation treatments, but did not require two applications, totaling 90 mm, of irrigation water in the dry year, and three applications, totaling 150 mm, of irrigation water in the normal rainfall and wet years. In addition, yield and oil production was significantly improved by RFFM and the application of a low total amount of 45 mm of irrigation water at the flowering stage in the dry and normal rainfall years. RFFM is thus a promising approach to improve crop production while conserving water. Moreover, RFFM can serve as an adaptive agronomic strategy and replace the conventional flat planting method in dryland agriculture to better sustain our food security and cope with the potential negative threats of climate change.

Acknowledgements

This work was supported by the National Key Research and Development Program of China (2016YFC0400201), the Special Fund for Agro-scientific Research in the Public Interest, China (201503125

and 201503105).

References

Bond, J.J., Willis, W.O., 1969. Soil water evaporation—surface residue rate and placement effects. Soil Sci. Soc. Am. Prod. 33, 445–448.

Cudennec, C., Leduc, C., Koutsoyiannis, D., 2007. Dryland hydrology in Mediterranean regions—a review. Hydrol. Sci. J. 52, 1077–1087.

Deng, X.P., Shan, L., Zhang, H., Turner, N.C., 2006. Improving agricultural water use efficiency in arid and semiarid areas of China. Agric. Water Manage. 80, 23–40.

FAOSTAT, 2016. FAO Statistics Division. Available from:. http://faostat3.fao.org./faostat-gateway/go/to/download/Q/*/E.

Gu, X.B., Li, Y.N., Du, Y.D., 2016. Continuous ridges with film mulching improve soil water content, root growth, seed yield and water use efficiency of winter oilseed rape. Ind. Crops Prod. 85, 139–148.

Gu, X.B., Li, Y.N., Du, Y.D., 2017. Optimized nitrogen fertilizer application improves yield, water and nitrogen use efficiencies of winter rapeseed cultivated under continuous ridges with film mulching. Ind. Crops Prod. 109, 233–240.

Gu, X.B., Li, Y.N., Du, Y.D., 2018. Effects of ridge-furrow film mulching and nitrogen fertilization on growth, seed yield and water productivity of winter oilseed rape (*Brassica napus* L.) in Northwestern China. Agric. Water Manage. 200, 60–70.

Hamzei, J., 2011. Seed, oil, and protein yields of canola under combinations of irrigation and nitrogen application. Agron. J. 103, 1152–1158.

Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A., 2001. Climate Change 2001: the Scientific Basis. Cambridge University Press, Cambridge.

Hu, W., Li, J., Sun, J., Chen, Y., Wang, X.C., Wang, M.Y., 2009. Simulation of grain yield and soil desiccation of spring wheat and corn fields in semiarid area of Loess Plateau. Res. Soil Water Conserv. 16, 149–161.

Jalota, S.K., Prihar, S.S., 1990. Effect of straw mulch on evaporation reduction in relation to rates of mulching and evaporativity. J. Indian Soc. Soil Sci. 38, 728–730.

Li, Q.Q., Chen, Y.H., Liu, M.Y., Zhou, X.B., Yu, S.L., Dong, B.D., 2008. Effects of irrigation and straw mulching on microclimate characteristics and water use efficiency of winter wheat in North China. Plant Prod. Sci. 11, 161–170.

Li, S.X., Wang, Z.H., Li, S.Q., Gao, Y.J., 2015. Effect of nitrogen fertilization under plastic mulched and non-plastic mulched conditions on water use by maize plants in dryland areas of China. Agric. Water Manage. 162, 15–32.

Mo, F., Wang, J.Y., Zhou, H., Luo, C.L., Zhang, X.F., Li, X.Y., Li, F.M., Xiong, L.B., Kavagi, L., Nguluu, S.N., Xiong, Y.C., 2017. Ridge-furrow plastic-mulching with balanced fertilization in rainfed maize (Zea mays L.): an adaptive management in east African Plateau. Agric. For. Meteorol. 236, 100–112.

Narayan, K.A., Schleeberger, C., Bristow, K.L., 2007. Modelling seawater intrusion in the burdekin delta irrigation area, north queensland, Australia. Agric. Water Manage. 89, 217–228.

Parry, M., Rosenzweig, C., Livermore, M., 2005. Climate change, global food supply and risk of hunger. Phil. Trans. R. Soc. B: Biol. Sci. 360, 2125–2138.

Payero, J.O., Tarkalson, D.D., Irmak, S., Davison, D., Petersen, J.L., 2008. Effect of irrigation amounts applied with subsurface drip irrigation on corn evapotranspiration, yield, water use efficiency, and dry matter production in a semiarid climate. Agric. Water Manage. 95, 895–908.

Piao, S., Ciais, P., Huang, Y., Shen, Z., Peng, S., Li, J., Zhou, L., Liu, H., Ma, Y., Ding, Y., 2010. The impacts of climate change on water resources and agriculture in China. Nature 467, 43–51.

Prentice, I.C., Farquhar, G.D., Fasham, M.J.R., Goulden, M.L., Heimann, M., Jaramillo, V.J., Kheshgi, H.S., Le Quéré, C., Scholes, R.J., Wallace, Q.W.R., 2001. The Carbon Cycle and Atmospheric Carbon Dioxide//IPCC. Contributions of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 183–238.

Qin, D.H., 2002. A Study of Environment Change and Its Impacts in Western China. Science Press, Beijing.

Qin, S.H., Zhang, J.L., Dai, H.L., Wang, D., Li, D.M., 2014. Effect of ridge-furrow and plastic-mulching planting patterns on yield formation and water movement of potato in a semi-arid area. Agric. Water Manage. 131, 87–94.

Ren, X.L., Cai, T., Chen, X.L., Zhang, P., Jia, Z.K., 2016. Effect of rainfall concentration with different ridge widths on winter wheat production under semiarid climate. Eur. J. Agron. 77, 20–27.

Rondanini, D.P., Gomez, N.V., Agosti, M.B., Miralles, D.J., 2012. Global trends of rapeseed grain yield stability and rapeseed-to-wheat yield ratio in the last four decades. Eur. J. Agron. 37, 56–65.

Shen, Z.R., Su, R.Q., 1998. Countermeasure of Agricultural Water Crisis in China. China Agricultural Science and Technology Press, Beijing, pp. 1–15.

Sun, W.C., Niu, J.Y., Teng, W.H., 2006. The effects of covering on winter-survival and yield of winter rapeseed. Chin. J. Oil Crop Sci. 28, 315–318.

Tian, Y., Su, D.R., Li, F.M., Li, X.L., 2003. Effect of rainwater harvesting with ridge and furrow on yield of potato in semiarid areas. Field Crop Res. 84, 385–391.

Wang, D., 2017. Water use efficiency and optimal supplemental irrigation in a high yield wheat field. Field Crops Res. 213, 213–220.

Wang, H.L., Zhang, X.C., Wei, S.W., 2015a. Impact of climate change on rain-fed farming and response solutions in semiarid area of northwest China. J. Agric. Resour. Environ. 32, 517–524.

Wang, Q., Ren, X., Song, X.Y., Hu, G.R., Zhang, E.H., Wang, H.L., Maureen, M.V., 2015b. The optimum ridge–furrow ratio and suitable ridge-covering material in rainwater harvesting for oats production in semiarid regions of China. Field Crops Res. 172, 106–118.

Yin, Y., Liao, X., Yu, B., Wang, H.Z., 2010. Regional distribution evolvement and development tendency of Chinese rapeseed production. Chin. J. Oil Crop Sci. 32, 147–151.

Zhang, S.J., Wang, H.Z., 2012. Policies and strategies analyses of rapeseed production response to climate change in China. Chin. J. Oil Crop Sci. 34, 114–122.

Zhang, J.Y., Sun, J.S., Duan, A.W., Wang, J.L., Shen, X.J., Liu, X.F., 2007. Effects of different planting patterns on water use and yield performance of winter wheat in the Huang-Huai-Hai plain of China. Agric. Water Manage. 92, 41–47.

Zhang, S.J., Liao, X., Zhang, C.L., Xu, H.J., 2012. Influences of plant density on the seed yield and oil content of winter oilseed rape (*Brassica napus* L.). Ind. Crops Prod. 40, 27–32.

Zhang, Y.Y., Han, H.K., Zhang, D.Z., Li, J., Gong, X.W., Feng, B.L., Xue, Z.H., Yang, P., 2017. Effects of ridging and mulching combined practices on proso millet growth and yield in semi-arid regions of China. Field Crops Res. 213, 65–74.

Zhou, H.M., Zhang, F.C., Kjelgren, R., Wu, L.F., Gong, D.Z., Zhao, N., Yin, D.X., Xiang, Y.Z., Li, Z.J., 2017. Peach yield and fruit quality is maintained under mild deficit irrigation in semi-arid China. J. Integr. Agric. 16, 1173–1183.